Invited Paper

Commercial Applications for COIL

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ABSTRACT

The chemical oxygen-iodine laser (COIL) is a high power, fiber deliverable tool, which can be used for a number of different industrial applications. COIL is of particular interest because of its short fiber deliverable wavelength (1.315 μm), high scaleable continuous wave (cw) power, and excellent material interaction properties. In past research the University of Illinois at Urbana-Champaign (UIUC) identified the decommissioning and decontamination (D&D) of nuclear facilities as a primary focus for COIL technology. D&D will be a major challenge in the coming decades. The use of a robotically driven fiber delivered cutting/ablation tool in contaminated areas promises to lower risks to workers for the D&D mission. Further, the high cutting speed of COIL will significantly reduce the time required to cut contaminated equipment, reducing costs. The high power of COIL will permit the dismantling of thick stacks of piping and equipment as well as reactor vessels. COIL is very promising for the removal of material from contaminated surfaces, perhaps to depths thicker than an inch. Laser cutting and ablation minimizes dust and fumes, which reduces the required number of High Efficiency Particulate Accumulator (HEPA) filters, thus reducing costly waste disposal. Other potential industrial applications for COIL are shipbuilding, automotive manufacturing, heavy machinery manufacturing, tasks requiring underwater cutting or welding, and there appear to be very promising applications for high power lasers in the oil industry.

1.0 INTRODUCTION

Lasers made their debut for materials processing in 1965. Since then, materials processing with CO_2 and YAG lasers has evolved into a mature technology [1]. Other laser technologies still evolving for materials processing applications are CO, excimer, HF/DF and the chemical oxygen-iodine laser (COIL) [2,3]. Of these other laser technologies, COIL is of particular interest because of its short fiber deliverable wavelength (1.315 μm), high scaleable continuous wave (cw) power, and excellent material interaction properties [4-6]. The combination of these characteristics suggests that COIL lasers will be well suited to applications needing high power and remote fiber optic delivery.

The short wavelength has three primary advantages over today's CO_2 lasers. First, the shorter wavelength of COIL can be focused to a smaller spot size. Second, the COIL wavelength couples better (higher absorption) with materials such as steel and aluminum. Third, experiments with a 1 kW COIL and 1-5 kW Nd:YAG lasers indicate that the wavelength can transmit through SiO_2 fiber optics with a loss of less than 1.0 dB/km [1,4]. While the capital and operating costs of today's first generation COIL devices may make them economically non-competitive with CO_2 devices in the low to mid power level markets, COIL has considerable potential for high power (> 5 kW) applications. Further, while Nd:YAG effectively has the same wavelength advantages as COIL, there are presently no YAG devices with average power levels in excess of 5 kW; this makes YAG non-competitive in the high power arena.

During the Air Force funded Small Business Technology Transfer (STTR) program to commercialize the chemical oxygen-iodine laser (COIL), the University of Illinois at Urbana-Champaign (UIUC)/STI Optronics team identified the decommissioning and decontamination (D&D) of nuclear facilities as a primary focus for COIL technology. Other researchers have established that COIL has a significant future as an industrial laser and have also identified D&D as an important market for COIL [7-10]. D&D will be a major challenge in the coming decades. The use of a remote fiber delivered COIL cutting/ablation tool in contaminated areas promises to lower risks to workers for D&D activities. Further, the high cutting speed of COIL will significantly reduce the time required to cut contaminated equipment, reducing costs. The high power of COIL will permit the rapid dismantling of complex handling equipment as well as reactor vessels. COIL is very promising for the ablation of material from

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contaminated surfaces, perhaps to depths thicker than an inch. Laser cutting and ablation minimizes dust and fumes, which reduces the required number of High Efficiency Particulate Accumulator (HEPA) filters, thus reducing costly waste disposal. Recent experiments [11] have demonstrated the usefulness of robotic laser cutting for the D&D mission. However, for the D&D requirements, more power will be required than that provided by an Nd:YAG laser.

Other potential industrial applications for COIL are shipbuilding, automotive manufacturing, heavy machinery manufacturing, tasks requiring underwater cutting or welding, and there may be useful applications in the oil industry. The building of capital ships involves the cutting and welding of very thick plates of metal. Heavy machinery manufacturers also work with thick plates of steel. It is possible to envision a single high-power COIL feeding many fibers for automotive cutting/welding applications [9]. Fiber delivered underwater applications appear very promising; it may be possible to use a high power, fiber delivered COIL beam to perform cutting/welding underwater and thus save the high cost of dry-docking a ship in need of repair. High power beams may also be of use in the oil and mining industries [60].

2.0 COMMERCIALIZATION ISSUES

The COIL research being conducted by UIUC and other international researchers, should lead directly to a new generation of commercial high power lasers. Our overall research goal is to demonstrate all necessary technologies for a revolutionary new chemical laser, COIL, which uses readily available chemicals in its subsystems. The differences between the requirements of a military and a commercial COIL system are listed in Table 1. Key research sub-topics which must be addressed are: 1) Efficient nitrogen nozzle technologies which will lead to low cost per photon; 2) Optical extraction and fiber delivery which will enable the use of COIL by industry; 3) Supporting technologies which will lead to long duration operation at a relatively constant power level.

Technology Issue	Military System	Commercial System
Efficiency	Power Per Unit Weight-Volume	Cost per Photon
Beam Propagation	Brightness on Target	Fiber Optics – Convenient Delivery
Duty Cycle	Peak Power, on Demand	Long Duration Average Power

Table 1. Technology issues associated with military and commercial COIL systems.

2.1 Novel Nozzle Mixing Systems

Several technological hurdles need be overcome before a packageable demonstration COIL system can be assembled and tested at a nuclear site. The highest chemical laser efficiencies of 27% have been demonstrated by Air Force Research Laboratory (AFRL) [12] using optimized supersonic nozzles and helium as the diluent gas. Similar efficiencies need to be achieved using alternate gases, such as nitrogen, which are more economically acceptable. Research in Russia has demonstrated chemical efficiencies 22.4% (798 Watts) with room temperature N_2 diluent [52]. In experiments with pre-cooled nitrogen, the Russian group initially demonstrated a chemical efficiency of 22% (200 Watts) [13] and more recently achieved a very high efficiency of 26% (236 Watts) [53]. The highest power level demonstrated by the Russian group using room temperature N_2 diluent was 1408 Watts with a chemical efficiency of 20.7% [52]. The Israeli group has demonstrated chemical efficiencies up to 17% [14] and 18% [54] without any primary diluent at a power level of 177 and 190 watts, respectively. A joint Russian and Japanese effort [15] produced a chemical efficiency of 23% (vs. 20% at room temperature) and 405 Watts with pre-cooled nitrogen diluent. Additionally, a novel supersonic injection into a supersonic stream concept was tested by the Russians that yielded 14% chemical efficiency and 130 Watts [8]. This high efficiency research shows very high promise for an industrial COIL, but until very recently had only been performed at a power level of a few hundred watts. While the Japanese have demonstrated a power level of 5 kW using nitrogen diluent, the chemical efficiency was only 15% [16]. The UIUC group recently demonstrated the highest chemical efficiency with room temperature nitrogen diluent of 23% [55] at a power level of half a kilowatt.

2.2 Fiber Optic Delivery

The COIL laser wavelength of 1.3 μm has a very low loss for silica fibers, indicating that remote flexible delivery systems for high power COIL lasers can be constructed. The loss for COIL wavelengths is even lower than the loss for Nd:YAG lasers at 1.06 μm, so that any developments for Nd:YAG lasers should be easily applied to COIL lasers. Commercial Nd:YAG lasers are available with 3 kW fiber optic delivery systems with 600 μm diameter fibers. The damage levels for cw Nd:YAG lasers indicate that powers of 10-15 kW could be delivered with a 1 mm core diameter silica fiber if the laser beam can be successfully coupled into the fiber. The potentially good beam quality available with COIL lasers should make coupling the power into the fiber easier than for lamp pumped Nd:YAG lasers, which suffer from thermal distortions in the crystalline solid state laser medium. Previous experiments by the Japanese at Kawasaki Heavy Industries had demonstrated a 1 kW COIL beam delivered through a fiber optic for materials processing [9]. These fiber optic delivery experiments show great promise for delivering higher powers for long run durations through a fiber optic, and for using the fiber delivered beam in a useful application.

The optical resonator design for a commercial COIL system needs further investigation. Most of the experiments to date on COIL lasers have used multimode stable resonators to extract the light from the gas in the cavity so that the potentially high beam quality is not realized. The typical active mode volume is rectangular because of the geometry of the nozzle and flowing gas, and does not interface well with circular optical fibers desired for remote beam delivery systems. Unstable resonators are typically used for extracting large gain volumes with good beam quality, but are difficult to employ for low magnifications for which the gain is low and the optimum outcoupling is also low. One solution is to employ a folded stable resonator to increase the gain length in conjunction with an intracavity circular aperture to provide a circular beam and severely limit the number of lasing modes. Another possible option is to use a graded reflectivity unstable resonator which has been successfully demonstrated for low magnification applications with both CO_2 and Ti:sapphire lasers. The trade-offs between different optical concepts and power output need to be studied to determine which will be optimal for coupling the highest power through a fiber optic.

2.3 Supporting Technologies

The supporting systems technology must be carefully considered for a commercial device [57]. The primary issues are the large quantity of chemicals required to fuel the laser and the size of the vacuum system required to maintain the low cavity pressure for the laser. A study of the potential for recycling the oxygen generator chemicals needs to be carried out. This will further reduce the size of the commercial system and have a big impact on the operational costs. Another issue of importance is the demonstration of long run times at high power levels. This can be accomplished by the recycling and replenishing of chemical in a continuous cycle as they are used [59].

3.0 APPLICATIONS FOR COMMERCIAL COIL

Potential industrial applications for COIL which have been identified are nuclear industry D&D [7-10], shipbuilding, automotive manufacturing, heavy machinery manufacturing, tasks requiring underwater cutting or welding, and there may be useful applications in the oil industry [60]. We will focus primarily on the D&D application in this paper, but also briefly discuss promising recent results for the oil and mining industry.

3.1 Significance of COIL to the Nuclear Industry

Entirely new technological methods must be introduced to process and deactivate the large numbers of nuclear reactor power stations now in place world-wide. Laser methodologies represent one of the more advanced techniques. Conventional cutting tools and CO_2 lasers lack several important attributes needed for rapid, remote, clean and safe cutting and processing of metals and other materials. The development of a commercial COIL device can provide the basis for a whole new generation of laser cutting and processing tools to government and industry. If successful, this will be the first major advance in high power laser cutting technology since the introduction of the CO_2 laser many years ago.

Fig. 1 shows the dramatically increasing number of such facilities which will need to be dismantled and replaced in ten to thirty years. Remote, clean operation with COIL laser systems can be a most significant new methodology in the D&D operations in this area.

The laser cutting technique has several advantages for dismantling and decommissioning projects because it can rapidly cut many materials, including iron, steel, stainless steel, aluminum, titanium, and concrete. It does not vibrate or produce any significant ejecta. The kerfs and heat affected zones are narrow so that distortion is minimized and minimal dust and fumes are produced; this in turn reduces the required number of HEPA filters. The cutting is not affected by the hardness of the material, and the wear problems of traditional tools are avoided. The cutting is fast and readily automated. Modern robotic techniques assure that the cutting path can be easily modified [11]. This flexibility allows one system to do many jobs from cutting, to coating removal, to ablation of surface materials with minimum modification to the tool. The system is readily adaptable to remote operation and robotics since the surface of the workpiece is not actually contacted by the tool and no reaction forces are generated. Most importantly, remote operation minimizes costly radiation exposure to personnel.

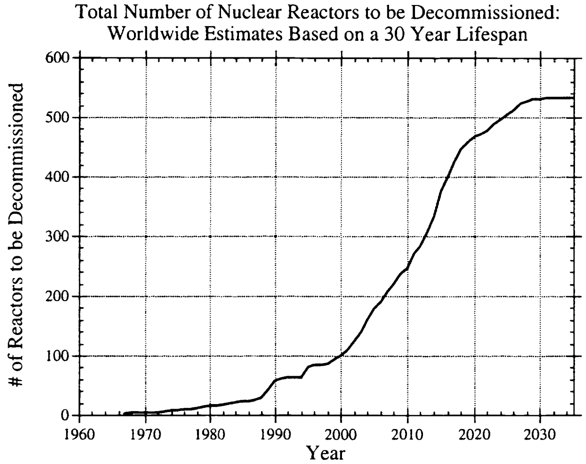

Fig. 1 Estimated number of reactors to be dismantled to the year 2035 (data compiled from Ref 17).

Our work at UIUC shows that the COIL chemical laser can be developed into a system that will allow delivery of continuous high power through a fiber optical system to a remote work area. Experiments performed last year by Sandia [11] with a low power (3 kW) fiber delivered Nd:YAG laser beam at the Sandia facility established the feasibility of working remotely robitically with precision robots and short wavelength lasers in hot cells. However, for many of the D&D requirements, it was clear that more power will be required than that provided by an Nd:YAG laser. The COIL laser seems ideally suited for the D&D mission. Cutting experiments with high powered COIL lasers which were carried out over the past few years at AFRL [5,6,43], provide rapid clean cuts on thick stainless steel, mild steel and aluminum structures. Our theoretical materials models confirm that the potential here is very high.

Another D&D application is that current nuclear fuel reprocessing technologies consist of a number of discrete stages: a head end process to dismantle fuel assemblies and expose the fuel (currently bulk shear); dissolution of the fuel; chemical separation of the fissile material; product finishing and treatment of the waste. The use of a bulk shear to dismantle the fuel results in all parts of the fuel assembly passing into the dissolution process, including the massive end appendages that provide the structural support of the assembly but contain no fissile material. BNFL [56] is currently working on future reprocessing technologies that require a more uniform sized feed from the dismantling process and necessitates the removal of the end appendages prior to shearing. A number of technologies were considered for the removal of the end appendages. BNFL concluded that a laser based system would provide a flexible cutting system capable of dealing with the wide range of assembly designs and also remove a lot of the problems inherent in mechanical cutting.

A typical LWR fuel assembly consists of up to a 17x17 array of fuel pins held in a square arrangement with a 200 x 200mm profile, Fig 2. The structural integrity of the assembly is provided by 6 to 8 zircaloy tie rods (10mm diameter) that are fastened to the end appendages and run the full length of the assembly. To remove the end appendages it is necessary to cut through the tie rods at the top and bottom of the assembly. However, in some cases the tie rods are hidden by the fuel pins and it may be necessary to cut all 289 fuel rods to expose a path to the tie rods. In summary, it is necessary for the laser to cut through solid zircaloy rod and hollow tube at a distance equal to half the total width of the assembly. At the position of the cut neither the fuel rods nor tie rods contain uranium oxide.

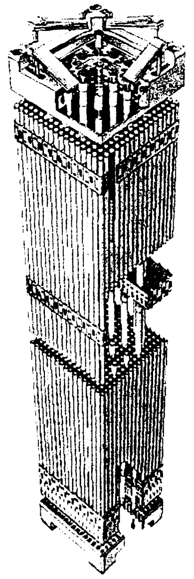

Fig. 2 Schematic of PWR fuel assembly.

3.2 Significance of COIL to the Oil and Mining Industry

Recent work by Graves and O'Brien [60] has demonstrated the ability of chemical lasers to significantly increase the rate of penetration (ROP) of rock drilling. A typical rotary drilled well has a ROP of roughly 23 ft/hr (6" hole diameter). Graves and O'Brien demonstrated an ROP of 166 ft/hr (6" hole diameter) and 450 ft/hr (2" hole diameter) using the DF MIRACL laser at the White Sands facility. Thus, roughly a factor of 10 improvement in ROP has been demonstrated using high power laser technology. Given that a typical ground oil well requires roughly 30 days to drill, a factor of 10 improvement in drilling speed would dramatically reduce labor costs. Drilling deep offshore wells using such high power lasers could result in enormous cost savings. Graves and O'Brien also indicate that laser drilling could reduce or eliminate casing requirements, bit life and trip time issues, and achieve these capabilities with environmentally attractive, safe and cost effective technology. Further, the use of high precision lasers "could eliminate many of the well control, side-tracking and directional (lateral) drilling problems which are often encountered in drilling or recompleting natural gas wells" [60]. COIL could play a significant role in these industries, both at the 10-30 kW level for smaller perforation size holes and at the megawatt level for conventional wellbore size holes (6" diameter).

4.0 INDUSTRIAL COIL DEVELOPMENT

The chemical oxygen-iodine laser was first demonstrated in 1977 [18]. Briefly, a chemical laser uses a series of chemical reactions to obtain excited atoms (or molecules) for subsequent lasing. The chemical oxygen-iodine laser (COIL) utilizes an energy transfer from the singlet delta electronically excited state of oxygen [$O_2(^1\Delta)$] to I_2 to dissociate the iodine molecule. This process is followed by an energy transfer from another $O_2(^1\Delta)$ molecule to the liberated iodine atom, thus providing the energy for the atomic iodine laser transition of interest. A typical supersonic COIL system is illustrated in Fig. 3.

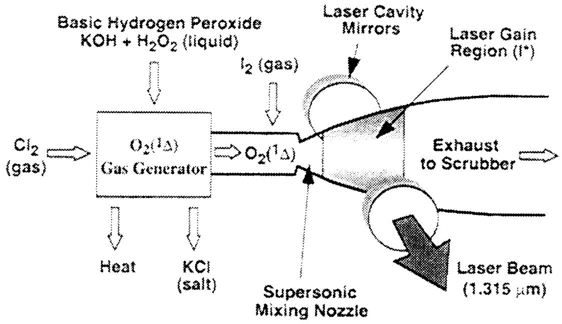

Fig. 3 Block diagram illustrating the major components of a typical COIL system.

Since its first demonstration, COIL technology has evolved and matured to a sophisticated state for military applications. An excellent summary of basic COIL operation and military COIL technological development is provided by Truesdell *et al.* [19]. In particular, the Air Force Research Laboratory (AFRL) has conducted nearly two decades of experimental and theoretical research with COIL. In 1987, the RotoCOIL device demonstrated 25 kW from a 54 cm gain length. Subsequently, powers up to almost 40 kW were demonstrated with 24% chemical efficiency [19]. Meanwhile, research towards making COIL an industrial device began in the latter half of the 1980's [20]. Long duration, low power industrial COIL operation has been demonstrated in recent years [12,21-25]. COIL uses standard industrial chemicals and the byproducts of reaction are benign salts, so disposal of spent chemicals is not a problem. Developing the technology to operate the device under turn-key conditions will significantly enhance the commercial appeal of this type of laser.

Japanese researchers at Kawasaki Heavy Industries have concentrated for several years on developing a COIL laser for industrial applications. They succeeded in building a 1 kW subsonic COIL laser that can operate continuously for times of the order of 1 hour at constant power [9]. AFRL has demonstrated over one hour run time at a fairly constant 500 Watt power level with the supersonic VertiCOIL device [12].

How does the status of COIL compare to other more mature industrial lasers? CO_2 lasers are well developed for materials processing applications. They are available with high power levels, good beam quality, and reasonable efficiency. However, their wavelength is too long for remote transmission through fiber optics and for good interaction with materials. CO lasers have been much less well developed for commercial applications, and are only available from a few manufacturers. They tend to be larger than similar power CO_2 lasers, and their main attraction is the better wavelength for interaction with materials. Nd:YAG lasers have also been available for many years, but are only recently becoming available with high enough power levels to be considered for industrial applications. Their short wavelength is attractive for better interaction with materials and for high transmission fiber optic delivery systems. However, the beam quality of lamp-pumped Nd:YAG lasers is poor, and the power into a 1 mm fiber is limited to ~2-3 kW due to thermal distortions in the solid state material. Diode pumped lasers may extend this power limit or alleviate the beam quality problems somewhat, but these high power diode pumped systems are still experimental. COIL lasers share the advantages of a short wavelength similar to Nd:YAG combined with an ease of scalability to high power and the potential for good beam quality due to their low pressure gas medium. Although the high-power scalability and high chemical efficiency of COIL has already been demonstrated, significant development is still needed to realize an efficient commercial COIL laser system.

The major advantages of COIL lasers over CO_2 and Nd:YAG lasers for materials processing are related to the wavelength (1.315 μm) and to the fact that COIL is readily scalable to high powers. Experimental data and theoretical calculations indicate that there is higher absorption by most materials as the wavelength of the laser decreases [26,27], resulting in higher cutting speeds for a given depth of cut and laser power.

In Phase II of the STTR program, the technology developed by AFRL was transferred to the U.S.A. private sector by assembling the VertiCOIL laser [12,25], Fig. 4, at UIUC to serve as a testbed for technology developments relevant to an industrial laser. As discussed earlier, military issues are different than commercial issues, Table 1. The transfer of the subscale VertiCOIL device to UIUC permits us to perform cost effective commercial technology development experiments. Testing of such technology issues on a subscale device makes economic sense; the results and knowledge from this practical experimental approach can then be directly inserted in the development of a large and efficient industrial scale device.

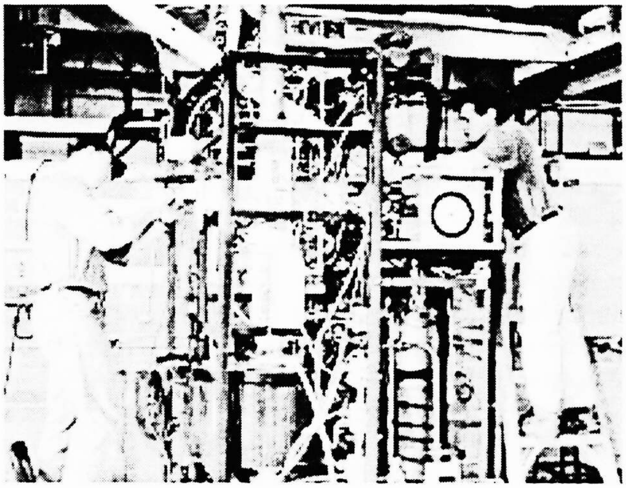

Fig. 4. The 2 kW VertiCOIL device setup at the University of Illinois.

5.0 MODELING AND PERFORMANCE

Every high power, high efficiency chemical laser in existence employs a converging-diverging nozzle to bring the primary flow to supersonic velocities. The primary flow typically carries the oxidizer plus a diluent (buffer) gas. A secondary stream carrying the fuel and more diluent is often injected into the primary at some point in the nozzle, either in the subsonic, sonic (or transonic), or supersonic part of the flow, Fig. 5. In chemical oxygen-iodine lasers, subsonic injection and mixing is typically used. COIL operation is strongly affected by the position of the mixing point along the flow. For the case of a COIL with nitrogen diluent, it may be preferable to carry out sonic (transonic) or supersonic injection. While the Israelis [54] have experimentally demonstrated 18% chemical efficiency in a COIL using transonic injection, the transonic mode of mixing has not yet been studied in detail.

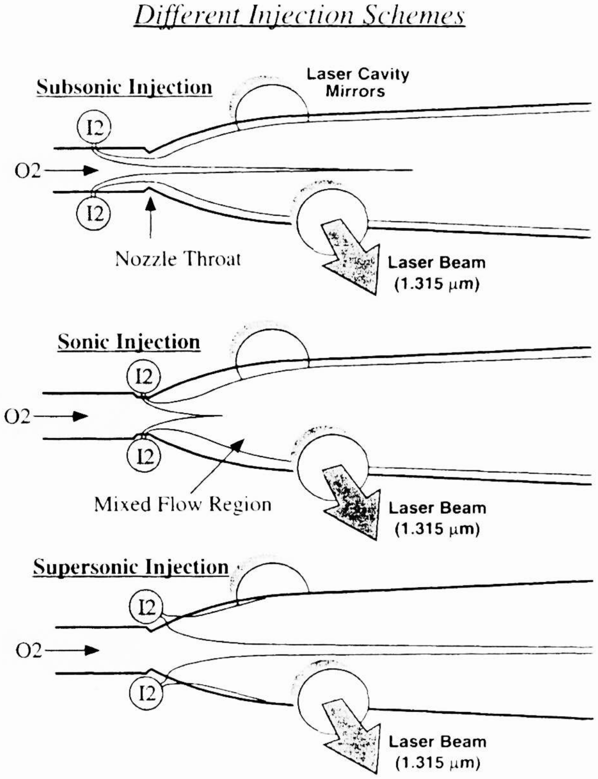

Fig. 5 Subsonic, sonic and supersonic injection schemes with an illustration of the mixed flow.

Quasi two-dimensional models for supersonic COILs were independently developed by Carroll at UIUC [28] and Barmashenko [29] in Israel and Yang at Rocketdyne [30]. These models were all in reasonable agreement with AFRL data [31-33] taken with the RADICL device.

While lower dimensional models are extremely useful for preliminary design calculations and parametric studies, the common drawback of both one and two dimensional models is that they cannot correctly model the nonuniformities in a 3D flowfield. It has been observed by many researchers that complete O_2/I_2 mixing is not achieved [13,14,34]. This observation has been confirmed by modeling studies conducted by UIUC and elsewhere; 3D Computational fluid dynamics (CFD) modeling [35-40] clearly shows that the iodine and oxygen densities are nonuniform across the flow in the resonator. These irregularities are created in part by the interaction of initially cylindrical iodine jets with the primary cross flow that results in the formation of a three dimensional horseshoe structure downstream of the injectors, Fig. 6 [39]. This structure stretches the contact surface between the chemicals and cannot be adequately predicted using one or two dimensional models. In order to fit the results predicted by lower dimensional models to the experimental data, the laminar diffusion coefficients are modified by an empirical diffusion coefficient multiplier (DCM) [28]. Correct simulation of mixing in COIL devices without any arbitrary assumptions can only be performed using three dimensional models.

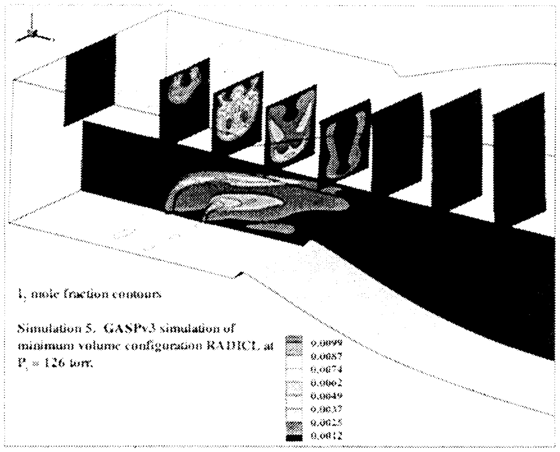

Fig. 6. Three dimensional perspective of the iodine jet in a COIL flowfield predicted by GASP (from Ref. 39).

Over the past six years, the UIUC has developed extremely advanced three dimensional COIL modeling capabilities. Numerous simulations of the AFRL's RADICL device have been performed [36-39]. The CFD code used by UIUC is a modified version of GASP [41] in partnership with AeroSoft, Inc. which solves the conservative, finite-volume formulation of the full Navier-Stokes equations coupled to a nonequilibrium chemistry model and a conservative, multicomponent diffusion model. A three dimensional simulation of the COIL flowfield was performed and compared to detailed gain distribution measurements. These detailed comparisons demonstrated that the model accurately predicted the experimentally measured distributions, a significant result in three dimensional simulation of reacting flows. An example of the calculated distributions of iodine in the flow are shown in Fig. 6 [39]. As discussed above, it is seen that the iodine jets develop a horseshoe shape.

For a commercial COIL, the use of nitrogen rather than helium diluent is of extreme importance for economical reasons and the fact that helium is a nonrenewable resource. The heavier molecular weight of nitrogen significantly slows down the flow velocity, increasing the residence time of the reactants in the subsonic flow region and consequently shifts the resulting laser gain zone upstream, i.e., the position of the gain zone changes with nitrogen use, Figs. 7 and 8. Thus, a nozzle optimized for power with helium diluent (as is the current VertiCOIL nozzle design) is not optimized for use with nitrogen diluent. Our research program is developing innovative nozzle designs optimized for nitrogen or no diluent by using our advanced computational tools.

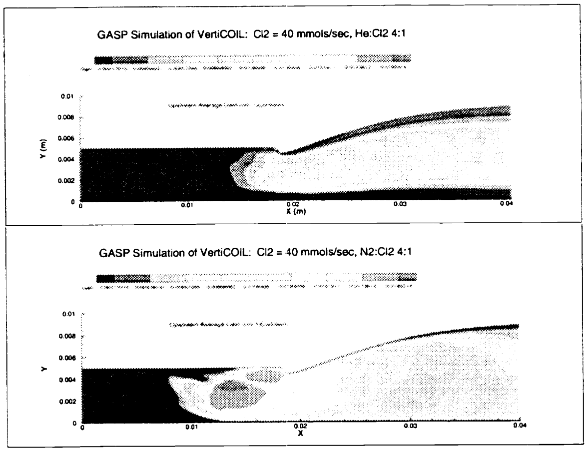

Fig. 7 GASP predictions of average gain for VertiCOIL flow conditions with helium (top) and nitrogen (bottom) diluent for 40 mmol/s flow rate of chlorine into the generator.

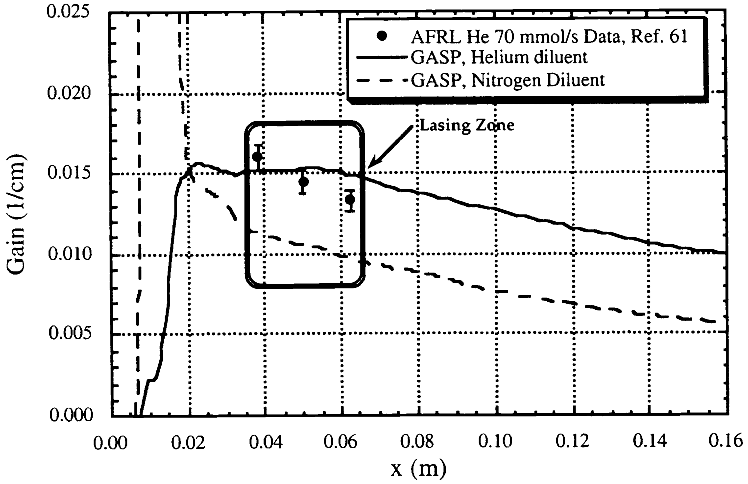

Fig. 8. GASP predictions of the maximum value of the average gain slice as a function of distance from the leading iodine injector for helium and nitrogen diluent for 70 mmol/s flow rate of chlorine into the generator.

To guide our nozzle design procedure, the Blaze II model [42] was used make predictions of how to change the nozzle design for optimal nitrogen diluent performance. The model had previously been baselined to RADICL gain data [43] and it was found that Blaze II overpredicted power measurements by an average of 33%; this is a consequence of using a Fabry-Perot model to simulate stable resonator data with some diffractive loss. Since the RADICL nozzle and the existing VertiCOIL nozzle are identical except for their gain length (10" for RADICL, 2" for VertiCOIL), the Blaze II baselining for RADICL should be appropriate for VertiCOIL. Using the conditions (flow rates, pressures, temperatures, mirror reflectivities, etc.) for which AFRL obtained a 27% chemical efficiency [12] with helium diluent as the starting point, calculations were performed with nitrogen diluent and 70 mmole/s of chlorine. The titration ratio β (=I2/O2) was fixed at 2.0%. Israeli work [14] indicated reasonable chemical efficiencies with injection at the throat; this led us to make computations of power as a function of injector location. For injection into the subsonic portion of the nozzle, it was found that moving the injectors closer to the throat significantly increased the predicted power, Fig. 9. This result is consistent with recent Russian experiments [13]. The nominal injector position has the leading edge of the large injector 1.12 cm upstream of the throat. Decreasing the separation between injector and throat to 0.22 cm progressively increased the predicted power. Further decreases in this separation caused difficulties for the Blaze II model which has a singularity at Mach 1. Regardless, the model indicates that it may be possible to obtain as high as 1750 Watts with 70 mmole/s of chlorine and nitrogen diluent. Given the previous Blaze overprediction of power, a more realistic power estimate is roughly 1313 Watts (=1750/1.33). Using the most common definition of COIL chemical efficiency [12,19],

$$chem.\,eff. = \frac{power(watts)}{90.0kJ\,mole^{-1} * Cl_2\,flow(mmoles/s)} \tag{1}$$

this power level corresponds to a chemical efficiency of approximately 21% using nitrogen diluent. Subsonic injection calculations were also made for other parameter variations such as penetration and mirror spacing. The penetration parameter was defined by Helms [32] to be,

$$penetration = \Pi = \frac{n_{sec}}{n_{pri}} \sqrt{\frac{MW_{sec} T_{sec} P_{pri}}{MW_{pri} T_{pri} P_{sec}}} \tag{2}$$

Variations in penetration produced no significant improvement in power; increasing the penetration to 0.20 improved the power to 1800 Watts, but this is nearly the same as 1750 Watts of the nominal penetration of 0.15 case (presented in Fig. 9). In Ref. [12] it was found that Π=0.156 was the optimal penetration using helium diluent. Decreasing the distance from the injection point to the start of the lasing region also slightly improved the predicted power up to 2000 Watts. After the 33% correction for Blaze II power overprediction, this corresponds to a chemical efficiency of 24%.

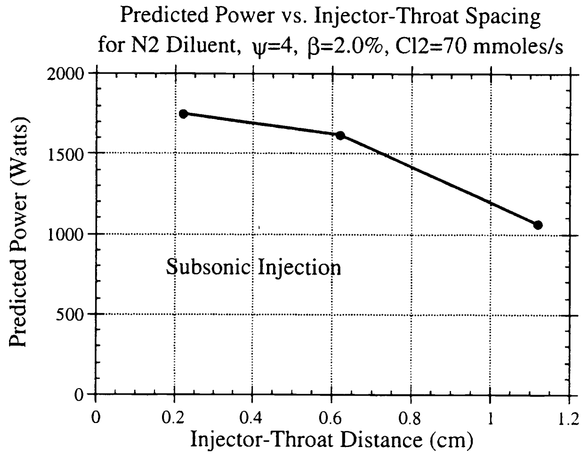

Fig. 9 Predicted VertiCOIL power vs injector-throat spacing with nitrogen diluent and subsonic injection.

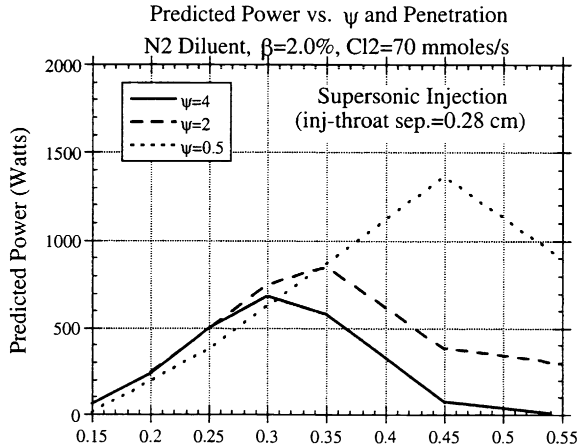

Fig. 10 Predicted VertiCOIL power vs diluent ratio and penetration with nitrogen diluent and sonic injection into a supersonic cross-flow.

Calculations were also performed for injection into the supersonic portion of the flow. Immediately it was found that the power dropped nearly to zero under nominal flow conditions. This was a consequence of the fact that the true penetration of a sonic jet into a supersonic cross-flow is not nearly as great as that into a subsonic cross-flow. To obtain significant mixing and penetration into the supersonic flow, two effects were tested. First, the penetration was increased by increasing the secondary diluent, and second, the penetration was increased by decreasing the primary diluent. Figure 10 illustrates that the best results occurred with high penetration and a very low primary diluent ratio of 0.5. Further decreases in diluent ratio ψ (=diluent/Cl2) produced no significant change. While the maximum power predicted with injection into the supersonic stream is much less, approximately 1350 Watts, it also corresponds to a very low diluent flow rate. The economical trade off between higher power with higher diluent flow and lower power with lower diluent flow needs to be examined. The predicted 1350 Watts corrects to 1015 Watts (=1350/1.33) which corresponds to a predicted chemical efficiency of 16%. The primary inhibitor to performance with supersonic injection appears to be a lack of mixing between the I2 and the high velocity O2 stream; this problem can likely be reduced or eliminated by a significant change in nozzle geometry. Further calculations indicated that a marginal performance increase could be obtained by moving the mirrors further downstream, which allows the mixed flow region to increase in size before extracting photons. Interestingly, these numerical results are very similar to recent Russian work [8] which demonstrated a 14% chemical efficiency with supersonic injection into supersonic primary flow and suggested moving the mirrors further downstream for their injection scheme.

6.0 COIL MATERIALS PROCESSING

During the STTR program to commercialize the COIL device, the UIUC participated in cutting experiments at the Air Force Research Lab (AFRL) to use the RADICL (Research Assessment, Device Improvement Chemical Laser) 5-7 kW laser to explore the potential for cutting thick steel with a COIL laser. Cutting rates obtained in these experiments [6] and in previous experiments at AFRL were compared with the rates obtained by other workers using CO_2 lasers. The results indicated that COIL laser cutting speeds were approximately 3-5 times faster than for comparable CO_2 lasers. With an oxygen gas assist, the cutting rate was at least a factor of three faster in carbon steel than with an inert gas assist. Cut depths of 20 mm were obtained in aluminum and 41 mm in carbon steel with an inert gas assist and 5-6 kW laser power on target. COIL cutting rates in aluminum were comparable to CO_2 cutting rates in steel, probably due to the much better interaction with the shorter COIL wavelength. Further experiments with a higher quality COIL beam produced high quality cuts through highly reflective aluminum and copper, as well as obtaining cutting data for inconel and titanium [44]. These cutting results indicate a significant advantage for COIL lasers in cutting thick metals as well as the ability to cut through highly reflective (and heat conducting) aluminum and copper.

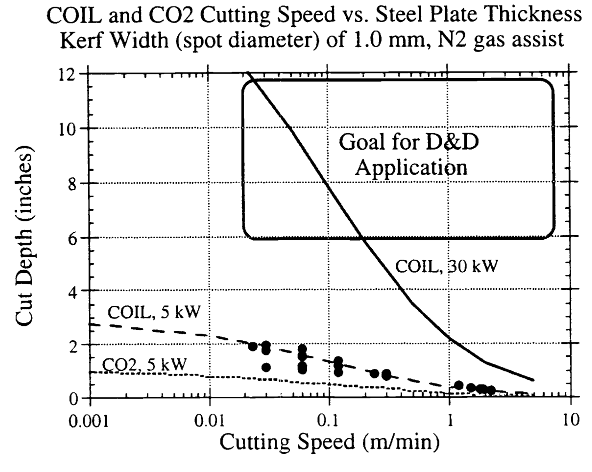

Fig. 11. COIL and CO_2 cutting speed as a function of steel plate thickness and device power. COIL cutting data for steel taken with RADICL are illustrated. A 10-30 kW COIL will be required for cutting apart 6-12" steel (experiements and theory from Refs. 5 and 6).

A theoretical cutting model was developed by Kar *et al.*[5] and modified by Carroll and Rothenflue [6]. As illustrated in Fig. 11, there is excellent agreement between the modified theory and the experimental data (slight fluctuations in the data are a result of scatter in the power level and beam size during the experiments). This modified model provides very good agreement with data for a variety of metals (stainless steel, carbon steel, aluminum, inconel, titanium and copper) [44]. We believe that the model can be used to make reasonable estimates of required cutting speeds for very thick pieces of metal.

These experiments and estimates from the theoretical model (see Fig. 11) determined that a 10-30 kW fiber delivered COIL should meet the needs of the nuclear decommissioning and decontamination efforts. A 10 kW COIL prototype followed by a 25 kW COIL laser module are the starting points for the modular construction of a high power industrial COIL laser. Higher laser powers can be produced by adding modules to the laser.

7.0 COMMERCIAL COIL DEVELOPMENT PLAN

As part of the STTR program, the UIUC successfully assembled and tested a 2 kW COIL device called VertiCOIL, Fig. 4. This testbed provides the UIUC with the research capability to test new components and new design techniques at a power level of interest and at an affordable cost. Experiments with VertiCOIL at UIUC are demonstrating 23% chemical efficiency using room temperature nitrogen diluent [55]. The UIUC has the capability to test new resonator designs to be coupled with a fiber delivery system. The flexible laboratory testbed is of sufficient size that a great deal of expansion can take place for different types of testing, including the construction of larger COIL devices.

In D&D operations such as cutting old contaminated reactors and pipes, it is desirable to have a mobile laser system that can move around from site to site. Figure 12 presents UIUC's latest concept for a mobile 10 kW COIL laser cutting system. The singlet oxygen generator, the laser nozzle and diffuser, the vacuum system, the basic hydrogen peroxide (BHP) cooling and recirculation system are all contained on one trailer. Supplies are shipped to the site by commercial vendors to resupply the tanks on the trailer. The only support that such a system will require is water and power (alternately the relatively small amount of power needed can be supplied from the diesel generator, as required). The laser power is delivered to the workpiece robotic cutting head with a fiber optic cable to minimize alignment problems and allow the laser to be delivered precisely to a contaminated workpiece.

An effective process for researching high power laser nozzles has been developed over several years at UIUC. Candidate concept nozzle systems are generically conceived and the logical parameter space is explored using a quasi-two dimensional fluids model called Blaze II [28,42]. Several variants of a particular concept are then compared under a variety of flow conditions. The peak performance of each particular concept is determined using an optimization routine, e.g., a Genetic Algorithm [43,45,46]. The final selected concept may be traded off against a competing concept or device, as a reality check. The basic nozzle dimensions, laser gains, and powers are obtained from this study. The quantitative non-equilibrium performance of each nozzle system is then determined by a rigorous CFD analysis. In most cases, we employ a series of codes to accomplish this task. The flow system is analyzed in 3-D using a modified finite volume Navier-Stokes solver GASP developed by Walters [41] and the data is delivered to a commercial package for post processing and calculation of the flowfield properties. All the relevent fluid parameters, velocities, temperatures, pressures, etc., and gain (the major laser performance parameter) in all three dimensions are simulated in the flow. Design concepts under investigation are the movement of the injectors just upstream of the throat, injection at the throat and mixing directly into the supersonic stream. They are shown conceptually in Fig. 5.

Another issue of interest to study is the recycling of the chemicals in order to further reduce operational costs. It is possible to implement and test such concepts at the UIUC chemical laser facility. Such testing at UIUC will answer important technological issues necessary to place the COIL system to the forefront of the currently nonexistent new high power, fiber delivered industrial laser market. These technological improvements will lead to an efficient, compact, and reliable high power, fiber-delivered laser.

The necessary fiber optics technology for remote delivery of the beam will need to be explored in depth. This will provide the best means of remote delivery of the laser beam for remote robotics type of operation envisioned for future applications. We will concentrate our efforts on improving the beam to provide maximum power as it couples into the fiber. Single mode fiber operation will be addressed to establish it's potential.

The data base for materials processing and cutting with our short wavelength COIL system needs to be enlarged. The data base required here is the materials which are potentially needed in the D&D mission. Ablation experiments should be performed to establish the capability of COIL to ablate thick layers of material, e.g., to what depth can material be ablated from a concrete block.

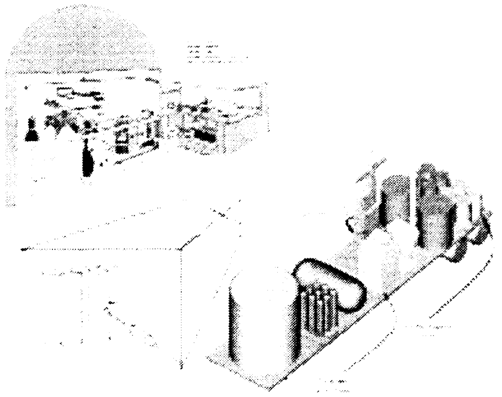

Fig. 12. Conceptual design for a mobile COIL demonstrator.

The most efficient form of generation of chemically excited oxygen (singlet delta) needs to be determined. Excited oxygen must be generated continuously in the intended application, as opposed to short bursts required for military applications. Presently VertiCOIL operates with a rotating disk generator [19,47,48]. Different types of generators could be tested, e.g., uniform droplet generator [49], or one of several different versions of the jet generator concept [50,51,58]. Of special interest here is a requirement for replenishing/recycling of the basic hydrogen peroxide (BHP) mixture in the most efficient manner. One possible scheme is to recycle the chemicals as they are depleted [59].

The key to maturing this research will be to establish workable subsystems technologies which will incorporate directly in a prototype commercial device. Testing of all the major components in an integrated experiment will represent the culmination of the numerical and experimental research effort.

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